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LASER PHASE FRONT MEASUREMENTS USING A PHASE CONJUGATE TWYMAN-GREEN INTERFEROMETER

THESIS

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THESIS

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Preface

The purpose of this study was to develop and demonstrate a phase conjugate Twyman-Green interferometer for use in measuring the phase fronts of the beams emitted by infrared lasers. This investigation used two infrared lasers: a single element diode laser and a multimode diode array laser. This interferometer successfully measured the phase front of the single element diode laser, but not that of the diode array. This method of phase front measurement proves to be more precise than conventional techniques when applied to a laser which is capable of creating a phase conjugate return, but it is not effective with the diode array which was not capable of creating a phase conjugate return.

In conducting this research and writing this thesis, I received invaluable assistance from others. I wish to thank my advisor, Dr. Won Roh, for his guidance throughout this progect. I also appreciate all the help I received from the laboratory technicians (Jim, Greg and Leroy). I owe a special thanks to my wife, Chris, who involuntarily, spent many long hours learning about phase conjugation.

William J. Mandeville

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Abstract

This study demonstrated the use of a phase conjugate Twyman-Green interferometer for measuring the phase fronts of beams emitted by infrared diode lasers operating at 830 nm. This interferometer successfully measured the phase front of a single element diode laser, providing better resolution than its conventional counterpart. The phase conjugate mirror compensated for aberrations introduced by imperfect optics in the phase conjugating arm of the interferometer. This interferometer was unable to measure the phase front of a diode array due to the array's inability to create a phase conjugate return. The array's short coherence length is believed to be the main cause preventing the phase conjugate return.

I. Introduction

Many applications exist that would greatly benefit from affordable, high power, light weight, durable lasers. Military applications for this type of laser could include communications equipment, range finders, night vision spotlights, anti-sensor weapons, and other applications which would benefit from light-weight, high power directed light. Laser diodes appear to be the answer.

Laser diodes, which are small semiconductor devices, "show great promise for military and commercial applications because of their size, efficiency, and ruggedness, but are limited in their output power due to facet damage at high output densities" [1]. Two ways to increase the power output from laser diodes without increasing the output density are (1) to increase the size of the facet area, and (2) to add more facets. Increasing the size of the facet area yields lasers with "uncontrollable transverse modes and poor wavefront quality" [1], so this approach does not effectively improve a laser diode's performance. However, increasing the number of facets appears to be a more promising solution. Laser diodes with multiple facets are known as diode arrays.

There are currently a variety of diode arrays available. These arrays may operate either coherently or incoherently: if the elements (the individual lasers making up the array) are close enough together on the chip so that evanescent waves out of each gain section can couple with their nearest neighbors, the array will operate coherently [1]; if the elements are not close enough for this to occur, the array will operate incoherently. Most arrays built today operate in high-order supermodes with twin-lobed far-field patterns [2]. The twin-lobed far-field pattern results from adjacent elements operating phase locked but 180° out of phase from each other [1]. This operating characteristic is not desirable because, instead of delivering the energy to a single spot, the laser spreads the energy into two primary lobes and many secondary lobes.

There is ongoing research which attempts to control the phasing between the elements of a diode array. This is done in an effort to concentrate the output into a single lobe and possibly to produce a beam which can be steered. In working to control the phasing of the elements, it is necessary to be able to measure the near-field phase front since any changes made in the phasing of the elements will show up in the near-field phase front. Interferometers are instruments which may be configured for this type of measurement. There is a class of interferometers that uses a non-linear optical process called phase conjugation, which has potential to make these measurements with greater resolution than conventional methods.

The research that has been done on phase conjugation has moved into the study of longer and longer wavelengths—leaving the visible and entering the infrared. Infrared phase conjugation is more difficult than visible phase conjugation because as the wavelength of the interacting beam approaches the infrared, the efficiency of photorefractive phase conjugation decreases. Phase conjugation has also been attempted with beams of various coherence lengths. Past research has shown that the shorter the coherence length the more difficult phase conjugation becomes. The direction of current research points to the development of diode arrays, many of which operate in the infrared and have short coherence lengths. Therefore it would be beneficial to develop a phase conjugate interferometer for measuring the phase fronts of these short coherence length, infrared arrays.

The main effort of the experiment reported in this thesis was to develop an interferometer which would be capable of measuring the phase front emitted by a diode array with better resolution than current methods. The interferometer examined in this work was a phase conjugate Twyman-Green interferometer, which is theoretically capable of twice the resolution allowed by conventional interferometers, due to its phase conjugate mirror. This type of interferometer was examined in hopes of aiding in the research to control the phasing between the elements of diode arrays. The main technical challenge in this work turned out to be producing a phase conjugate return from the array using Barium Titanate ($BaTiO_3$).

First this thesis will discuss the basic theory of phase conjugation. Next it will summarize previous work in phase conjugate interferometery in order to provide a context for the research presented here. This summary will also present two conventional methods for the measurement of the phase fronts emitted by diode arrays. Next, the procedures section will describe the lasers and interferometers used in this thesis and how they were configured. Finally, the results will be presented and discussed, and conclusions drawn.

II. Theory

This section will address the fundamental theories and principles necessary to understand how the phase conjugate interferometer used in this experiment differs from a conventional interferometer (i.e., an interferometer without a phase conjugate mirror). First, a description of a phase conjugate interferometer along with its superior resolution capability over conventional interferometers will be given. Next, the implications of a phase conjugate mirror will be discussed. Finally, there will be a brief description of the physics involved in phase conjugation.

Interferometers are tools which can be used to reveal information about waves. The experiment reported in this thesis employed interferometers for the measurement of the phase fronts emitted by lasers. To measure the phase front of an input wave, a certain kind of interferometer may be used which divides the input wave into two amplitude parts. This type of interferometer is referred to as an amplitude splitting interferometer. One of the two waves is altered to produce a reference wave which has a known phase front. The phase front of the other wave remains unchanged, and thus carries the information about the phase front of the original wave. This second wave is known as the test wave. To determine the phase front of the test wave, the interferometer interferes it with the reference wave, creating an interference pattern. It is the difference between the phases of the reference wave and the test wave that causes the interference pattern. This interference pattern may be analyzed to reveal the phase front of the original wave. To increase the sensitivity of an interferometer, the difference must be increased between points along the reference wave and the corresponding points along the test wave. Conventional interferometers commonly use plane waves as the reference wave. To increase the resolution, instead of a plane wave, a wave which has an inverted replica of the test wave could be used as the reference wave. If this is done, the difference between the test wave and the reference wave will be twice what it was when the plane wave was the reference wave. This concept is shown graphically in Figure 1. In order to produce this inverted phase front, a component known as a phase conjugate mirror must be integrated into the interferometer.

A phase conjugate mirror is the key component of a phase conjugate interferometer which enables it to provide greater resolution for phase front measurements than do its conventional counterparts. Phase conjugation is a non-linear optical process which both inverts a phase front and reverses its direction of propagation [3]. A conventional mirror is not capable of inverting the phase front. An illustrative example of the properties of a phase conjugate mirror are shown in Figure 2. As depicted in the figure, diverging light emitted from a point source is redirected by a conventional mirror and continues to diverge. In contrast, when a phase conjugating mirror is struck by diverging light, a "converging conjugate wave [is created] that precisely retraces the path of the incident wave" [3]. The example illustrated in Figure 2 uses a spherical phase front. However, a phase conjugate mirror is capable of inverting a complex phase front as well.

Phase conjugate mirrors not only have the ability to invert the phase front, they also have the added benefit of causing unwanted aberrations to cancel themselves out. As an illustration of this property, Figure 3 shows a plane wave passing through a plate. The central region of this plate has a higher index of refraction than the rest of the plate, so it will take the light longer to pass through this area. Therefore the phase front which passes through the central region will be *retarded*. When the phase conjugate mirror reflects the light, it reverses and inverts the phase front, thereby returning the phase front with the central region *advanced*. Now, when the phase front passes back through the same plate, the portion of the phase front passing through the central region—now advanced—will once again be *retarded*, restoring the plane wave to its original state. In contrast, if a plane wave passed through the same plate and struck a conventional mirror, the phase front

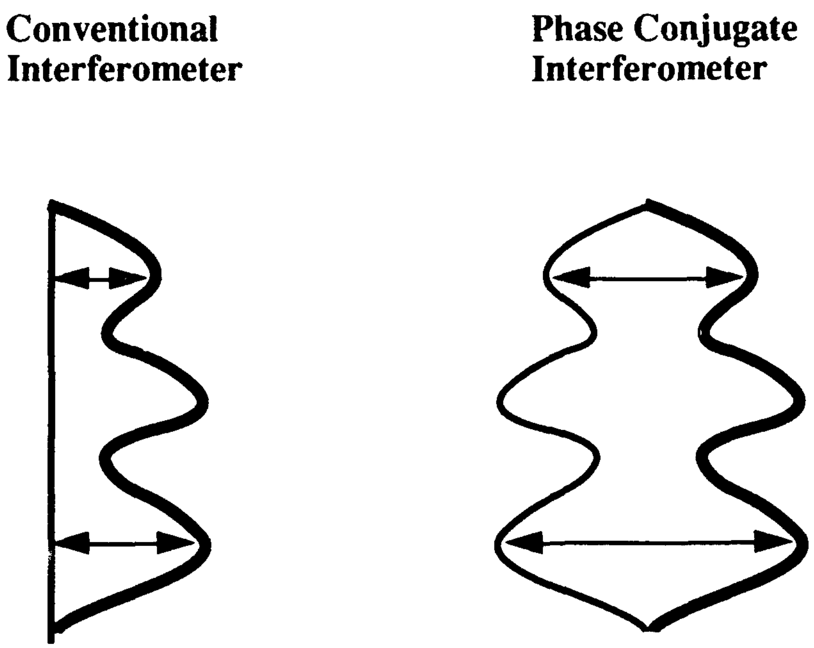
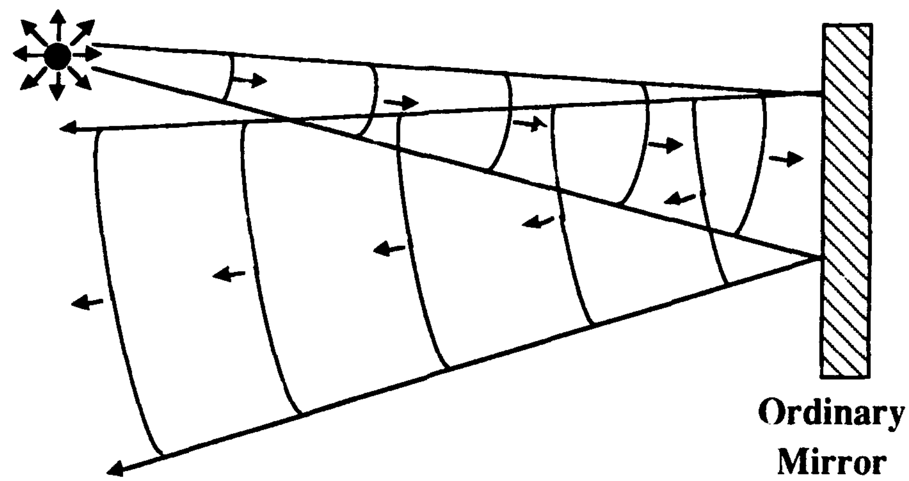


Figure 1. Conventional interferometers use plane waves as reference waves. A phase conjugate interferometer has the ability to generate an inverted phase front to be used as the reference wave. This difference is what allows the phase conjugate interferometer to have twice the resolving ability of a conventional interferometer.



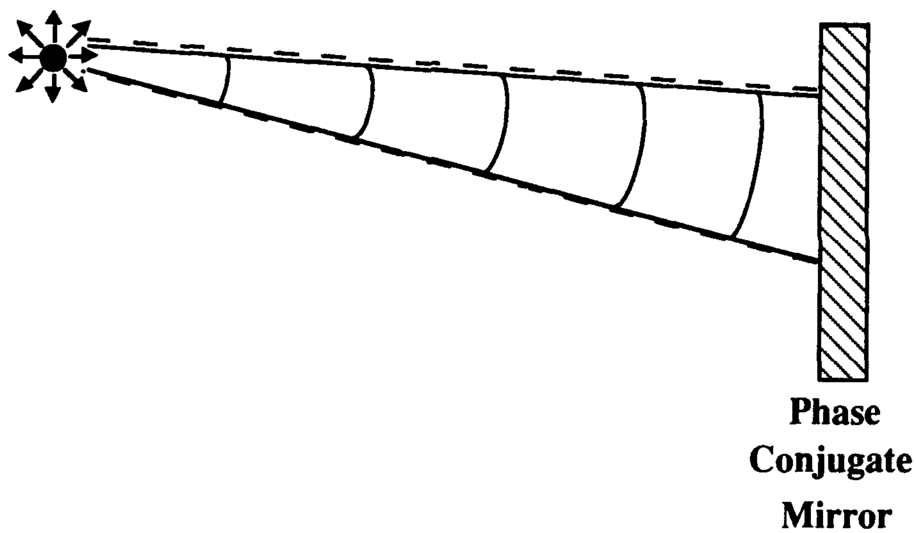


Figure 2. Comparison of the spatial properties of a phase conjugate mirror with that of a conventional, plane mirror. Both mirrors are illuminated by a point source. Whereas the reflective properties of an ordinary mirror merely redirect the propagation direction of the diverging beam, the phase conjugate mirror "reflects" the light so as to exactly retrace the incident wave in a "time-reversed" sense. The conjugate wave's equiphase surfaces overlap with those of the incident wave [3].

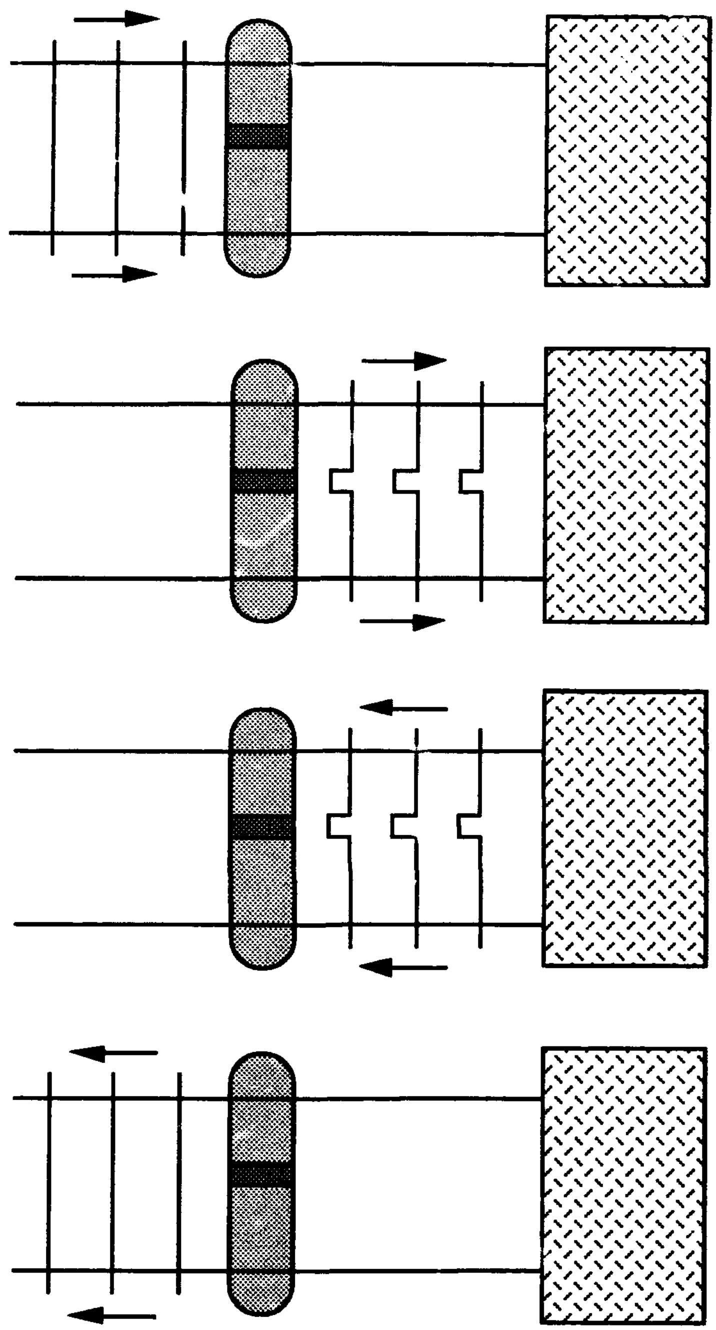


Figure 3. Results of two passes through a non-homogeneous window and reflection off of a phase conjugate mirror. The darker shading represents a region of higher index of refraction. The phase conjugate mirror has the ability to compensate for aberrations caused by non-precision optics.

would be redirected but not inverted. Thus, the central region would still be retarded when the wave passed through the plate the second time. The region of higher index would further retard the central portion of the phase front, thereby doubling the effect of the aberration. See Figure 4. Therefore, if a phase conjugate mirror is integrated into an interferometer, an inverted phase front can be created for the reference wave and the quality of the optics preceding the phase conjugate mirror are unimportant, making it possible to use less expensive optics in an interferometer with higher resolution.

The interferometer discussed in this thesis used a photorefractive material for the phase conjugate mirror. A photorefractive material is a material whose optical properties change when exposed to light. In a phase conjugate mirror, the optical properties of the material are changed in such a way as to produce a unique transmission and/or reflection grating capable of creating a phase conjugate wave. The process of light altering the optical properties of a photorefractive material to set up this grating is summarized in the following six steps by David Pepper [4]:

1. Two laser beams interfere in a photorefractive crystal to form a pattern of bright and dark regions.
2. Mobile electrons migrate away from bright regions of the crystal.
3. Mobile electrons accumulate in the dark regions, leaving regions of positive charge.
4. An electric field forms between regions of positive and negative charge.
5. The electric field distorts the crystal lattice.
6. The distortion causes light to travel slower through some regions and faster through others. More specifically, the refractive index is altered periodically. The refractive-index grating is shifted one quarter of a period in space from the light pattern.

The crossing beams required for step one can be provided by a number of arrangements. In this thesis research a single beam was used to produce the interference inside the crystal. This type of phase conjugation is known as self-pumped phase conjugation. Self-pumped phase conjugation was initially accomplished by using two or more external mirrors to bend the beam causing it to cross itself inside the crystal. These mirrors were arranged in a configuration called a ring cavity. Figure 5 shows two common

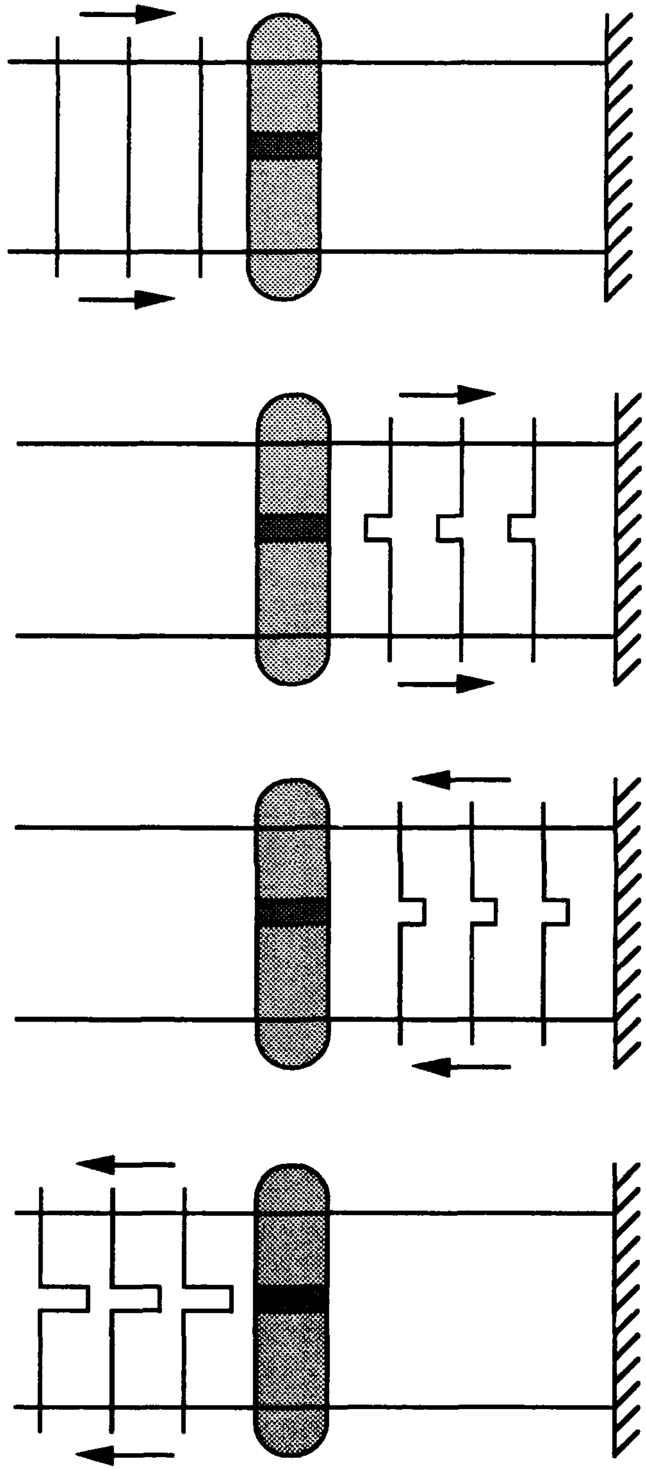


Figure 4. Results of two passes through a non-homogeneous window and reflection off of a conventional mirror. The darker shading represents a region of higher index of refraction. The conventional mirror doubles the effect of the aberrations caused by non-precision optics.

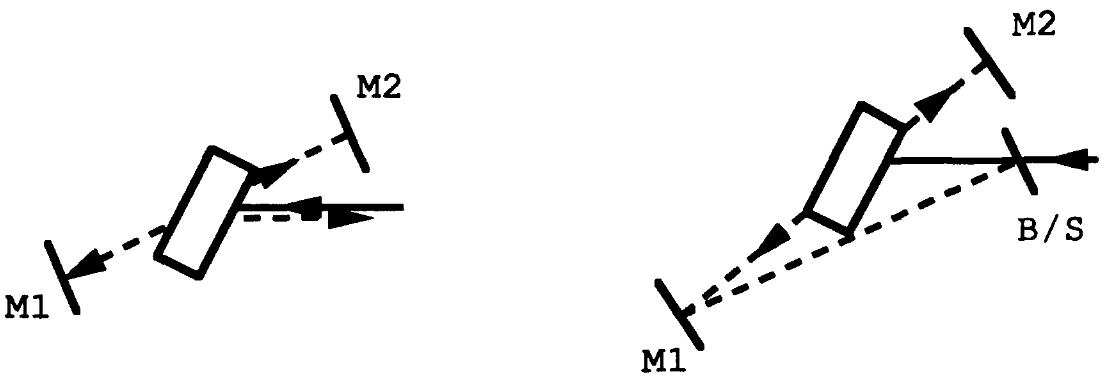


Figure 5. Two common ring cavities. The external mirrors serve to bend the beam back into the crystal where it can interfere with itself for phase conjugation.

ring cavities. More recently, a simpler geometry has been explored which uses the internal reflection of the crystal to bend the beam back on itself. See Figure 6. The use of external mirrors has the disadvantage of requiring careful alignment of the mirrors and a longer coherence length than does the method of using internal reflections. If the path the beam travels before crossing itself inside the crystal is more than one coherence length, the beam will not interfere with itself and phase conjugation will not occur. Since the research presented in this thesis was interested in phase conjugating a laser array which has a very short coherence length, ring cavities were not considered.

The photorefractive material used in this research was barium titanate ($BaTiO_3$). In a $BaTiO_3$ crystal, the photorefractive effect manifests itself as the beam fanning in the direction of the crystals' c-axis. Two types of cuts of the crystals were used in this research. In one type , the c-axis is parallel to one of the faces and is said to be a z-cut crystal. In the other, the c-axis passes diagonally across the crystal, and is said to be a 45°-cut crystal.

This section has attempted to develop a basic understanding of what phase conjugation is and why enhanced resolution was expected for the interferometer used in the research presented in this thesis. The next section will present a brief review of previous research relevant to the present experiment.

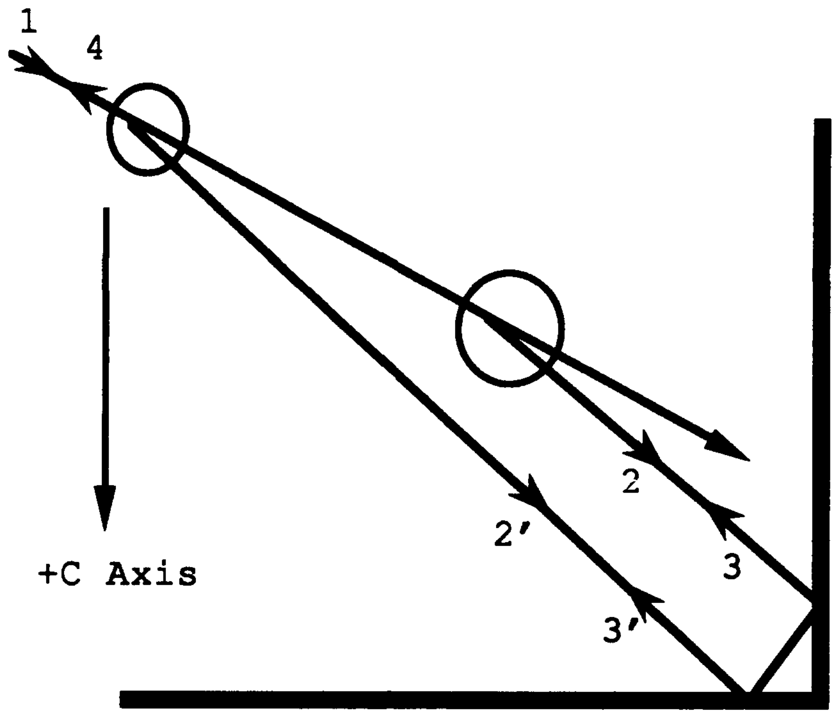


Figure 6 The incident beam (1) enters the crystal from top left. Beam 2 splits off and is internally reflected twice near the crystal edge and becomes beam 3', which then intersects beam 1 slightly upstream. Beam 2' has also split off from beam 1 and travels around the loop in the opposite direction. Beams 1-3 generate beam 4 by four-wave mixing in the interaction region circled on the right, as do beams 1,2', and 3' in the interaction region circled on the left. Beam 4 is the phase-conjugate replica of beam 1, and it leaves the crystal exactly back along the direction of the incident beam [6].

III. Previous Work

This section will review the evolution of achievements in self-pumped phase conjugation using $BaTiO_3$. The evolution of this work leads to and motivates the research presented in this thesis. First, the evolution of self-pumped phase conjugation will be presented as it proceeds from the visible into the infrared. Second, this section will review the utilization of phase conjugate mirrors in the field of interferometery. Finally, two currently used conventional methods of measuring the phase fronts of diode arrays will be presented.

Advancements in Phase Conjugation

Prior to 1981, phase conjugation required one or more external pump beams. In 1981 Jeffrey White, et. al. was the first to demonstrate phase conjugation without an external pump beam. They described several geometries by which self-pumped phase conjugation could be accomplished. All of these geometries required at least two external mirrors configured in a ring cavity. This work was done using a helium neon laser with a wavelength of 632.8 nm [5].

In 1982 Jack Feinberg reported self-pumped phase conjugation without external mirrors configured in a ring cavity. This work was done using an argon-ion laser operating in the visible at 514.5 nm. The geometry he used is shown in Figure 6 [6].

The following year Mark Cronin-Golomb and Kam Y. Lau reported the first photorefractive phase conjugation achieved in the infrared. This was the first time a semiconductor laser was combined with the beam handling and distortion correction capabilities of a phase conjugate mirror [7]. The laser they used was a GaAlAs laser operating at 815 nm. Their experiment used a ring cavity with two external mirrors.

Six years after Cronin-Golomb and Lau achieved phase conjugation in the infrared using a ring cavity, Ike Bendall and Debra Gookin, while working at the Naval Ocean

Systems Center, succeeded in phase conjugating an 830 nm semiconductor laser without using external mirrors [8]. In their experiment, they immersed the $BaTiO_3$ crystal in a glycerol bath which served as an index buffer, allowing them to overcome the low infrared efficiency of the phase conjugating crystal [8]. An index buffer was also used in the research presented in this thesis and will be discussed in more detail later.

Phase Conjugate Interferometers

With the advent of phase conjugate mirrors, interferometers were developed that exploited their unique properties. Some milestone interferometers are described below.

In 1983, one year after he reported phase conjugation without a ring cavity, Jack Feinberg demonstrated the first self-pumped phase conjugate interferometer [9]. The interferometer he demonstrated was a Michelson's interferometer. The advantage of phase conjugation in this interferometer was that it could detect motion and a uniform phase shift in the arm containing the phase conjugate mirror, while automatically canceling turbulence and distortions found in the beam path [9].

In 1988, Daniel Gauthier and Robert Boyd developed a phase conjugate Fizeau interferometer [10]. They found this interferometer to be self-referencing and to provide a twofold improvement in sensitivity over conventional interferometers [10].

In 1989, Shukla et al. demonstrated a phase conjugate Twyman-Green interferometer designed for optical testing [11]. They used this interferometer to test a concave spherical mirror and to measure the refractive index of a liquid [11]. The development of this interferometer eliminated the need for large precision mirrors in the reference arm, thus reducing the cost significantly for the testing of large optics.

The research to be presented in this thesis attempted to use a phase conjugate Twyman-Green interferometer similar to the one used by Shukla to make phase front measurements of an infrared diode array. This interferometer is expected to allow better resolution than the conventional interferometers for this type of measurement. Two current methods of making this measurement are presented below.

Phase Front Measurements of Diode Arrays

One method for measuring the phase fronts emitted by diode array lasers was developed in late 1986 by Gregory Dente. His innovative technique scanned a mask with two slits in it across a magnified near-field image of the array. As this mask moved the Young's fringes in the interference pattern would shift. By analyzing this motion, it was possible to determine the near-field phase profile of a diode array. This method requires complicated analysis of the moving interference pattern.

The most conventional method for measuring the phase fronts of diode array lasers is known as shearing interferometery. The shearing interferometer was used as early as 1985 by Yaeli to obtain far-field interference data [12]. In 1990, Chemg et al. made the first measurements of the near-field phase front of a diode array with a shearing interferometer [13]. This technique is superior to the double slit method described above in two ways: there are no moving parts during the data collection period, and all fringe data is recorded simultaneously so turbulence and vibrations will not effect the results [13].

IV. Experimental Apparatus

This section will focus on the lasers and interferometers used in this research. There were three lasers available for this research: an argon-ion laser, a single element diode laser, and a ten element diode array. Each provided a different degree of difficulty for phase conjugation. There were two types of interferometers employed in this research: a Twyman-Green interferometer, and a Mach-Zehnder interferometer. The Twyman-Green interferometer was set up in both a conventional and a phase conjugate configuration. This section will discuss the three lasers, present the configuration of the interferometers, and describe how the interferometers were used to collect data.

Lasers

Argon-ion.

The argon-ion laser, Ion Laser Technology Model 5490AWC, operates multimode at 514.5 nm and has an output power of approximately 50 mW. This laser was not difficult to phase conjugate due to its visible wavelength. The visible beam of this laser was easy to align and the effects of phase conjugation inside the crystal were easy to observe. This laser was used to determine the orientation of the c-axis of the crystals and also to determine the response characteristics of each crystal. This laser served the purpose of familiarization with phase conjugation.

Sharp Diode.

This single element diode laser was manufactured by Sharp as an index-guided laser, operating in a single transverse mode. Its model number is LT015MD/MF. This laser is made of AlGaAs and lases at 830 nm with an output power of 40 mW. The fact that this laser operates in the infrared makes it more difficult to phase conjugate than the argon-ion laser. This laser was used to determine if phase conjugation would work at 830 nm.

SDL Diode Array.

Spectra Diode Labs laser, model SDL-2410-C, is a multiheterojunction AlGaAs diode laser array. It has ten gain-guided active elements lasing at 830 nm. This device was designed as a multiple longitudinal mode device which exhibits a twin-lobed far-field radiation pattern. This laser was expected to be the most difficult to phase conjugate due to its infrared wavelength and its short coherence length (~1 mm). Developing a phase conjugate interferometer capable of measuring this laser's phase front was the goal of the research presented in this thesis.

Interferometers

Conventional Twyman-Green.

Coherence length measurements were made with a conventional Twyman-Green interferometer. Figure 7 shows the configuration of this interferometer. In a Twyman-Green interferometer, the input beam is split at the beam splitter, then each beam strikes a turning mirror at near normal incidence and returns to the beam splitter. If the paths the two beams travel differ by less than one coherence length, the two beams will interfere at the beam splitter creating two interference patterns. One pattern will travel toward the observation point while the other travels back toward the source. These two patterns will be complimentary in intensity (i.e., where one is bright the other is dark and vise versa). If one of the mirrors is tilted relative to the other, a series of parallel fringes will appear in the interference pattern. To measure the coherence lengths of the lasers, both flat mirrors are initially positioned equidistant from the beam splitter. The coherence lengths of the lasers can be determined by moving one of the mirrors back until interference is no longer be detected. The distance the mirror is moved represents one half the coherence length of the laser being tested. This interferometer is not capable of determining the shape of a phase front since neither beam acts as a reference wave.

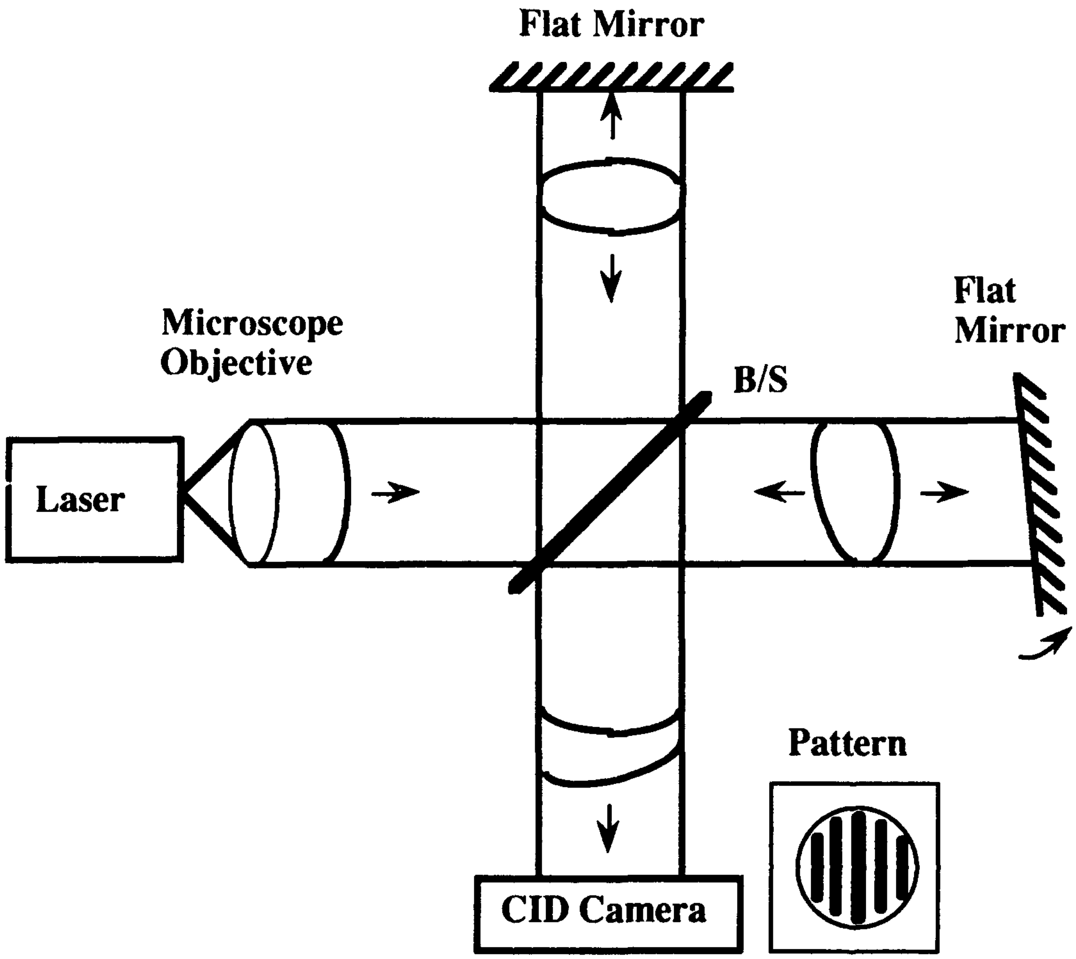


Figure 7. Basic Twyman-Green Interferometer. This interferometer is shown detecting tilt. This interferometer is only capable of determining relative differences between the two mirrors. It is not capable of determining the shape of the phase front of the input beam.

Phase Conjugate Twyman-Green.

Unlike its conventional counterpart, a phase conjugate Twyman-Green interferometer is capable of making phase front measurements. A phase conjugate Twyman-Green interferometer is shown in Figure 8. The difference between this interferometer and the conventional Twyman-Green interferometer is that one of the flat mirrors is replaced by a phase conjugating mirror. The beam which strikes the conventional mirror has its direction of propagation reversed. The beam in the phase conjugate arm also has its direction of propagation reversed by the phase conjugating mirror. However, the phase conjugating mirror also serves to invert the phase front making it a reference wave. As in the conventional version, when the two beams recombine at the beam splitter they will interfere with one another. The interference pattern which is created reveals the shape of the phase front. The best contrast is achieved when the optical path length for the two arms is equal and the intensity of the two beams is adjusted to be the same. The optical path length can be adjusted by translating the flat mirror, which is more easily accomplished than moving the phase conjugate mirror. The intensity of the beam coming from the flat mirror can be reduced to match the intensity of the beam coming from the phase conjugating mirror using a variable neutral density filter.

The system (depicted in Figure 9) was used to test the ability of the three lasers to phase conjugate. An optical isolator was used to prevent the retro-reflection from the crystal from affecting the laser. A polarization rotator was used to provide the extraordinary ray required for the crystal. A beam splitter was set up to separate the returning, conjugated beam from the original beam so it could be viewed.

Mach-Zehnder.

A Mach-Zehnder interferometer was used as a conventional reference for measurement of the phase fronts. The Mach-Zehnder interferometer was set up as shown in Figure 10. This interferometer used a plane wave as the reference beam. This plane wave was created by implementing a spatial filter with a 25 mm pinhole. A collimating lens

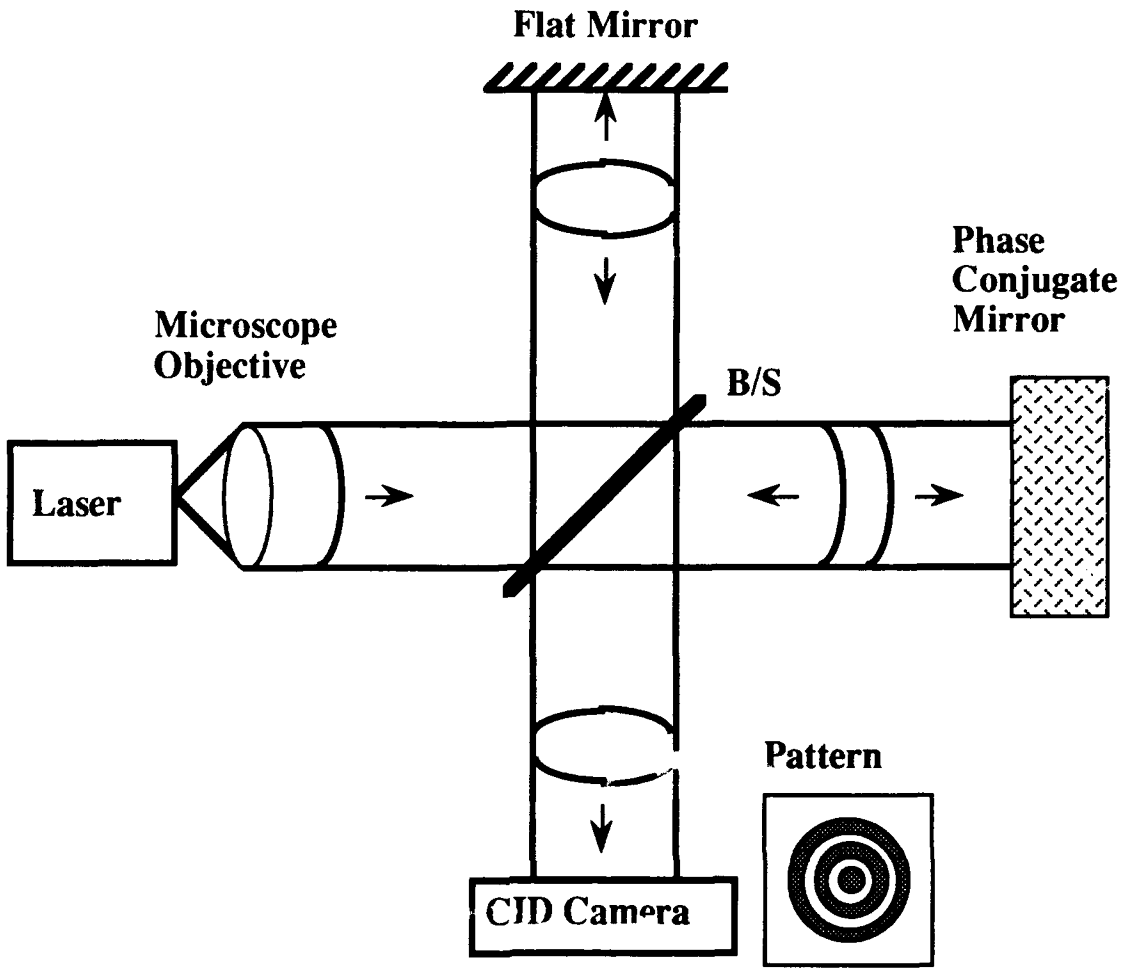


Figure 8. F ase conjugate Twyman-Green Interferometer. This interferometer may be used to determine the shape of the phase front of the input beam. This interferometer allows twice the resolution of the Mach-Zehnder interferometer.

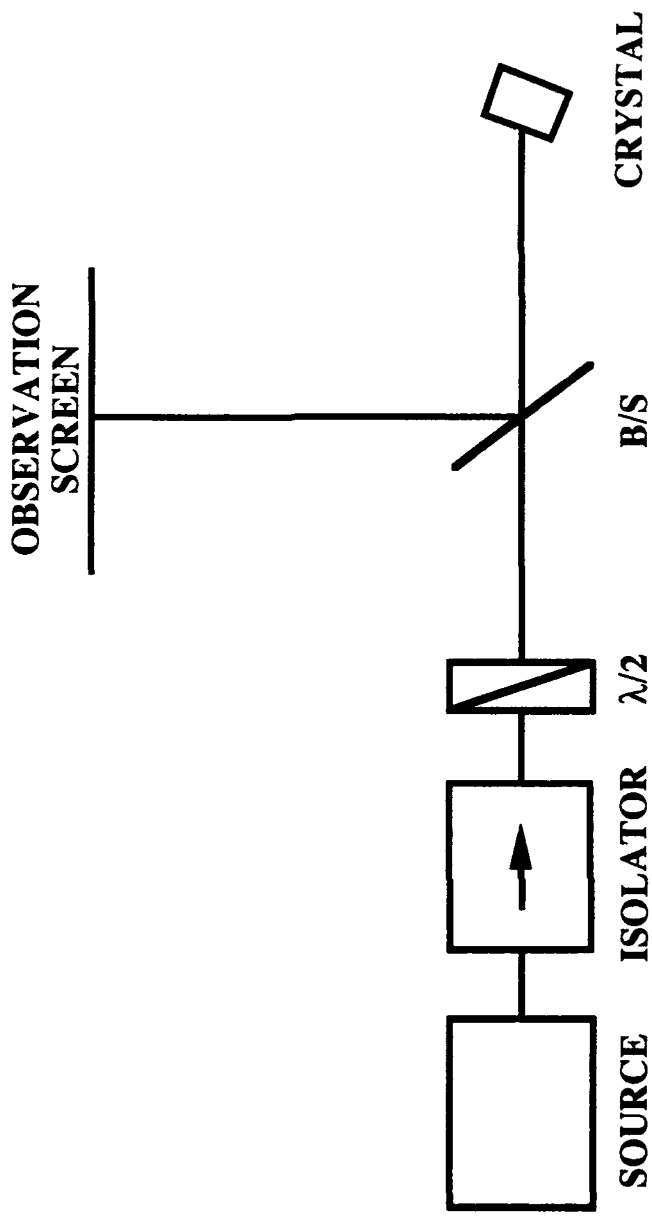


Figure 9. Experiment which was used to determine the phase conjugating abilities of the $BaTiO_3$ crystals.

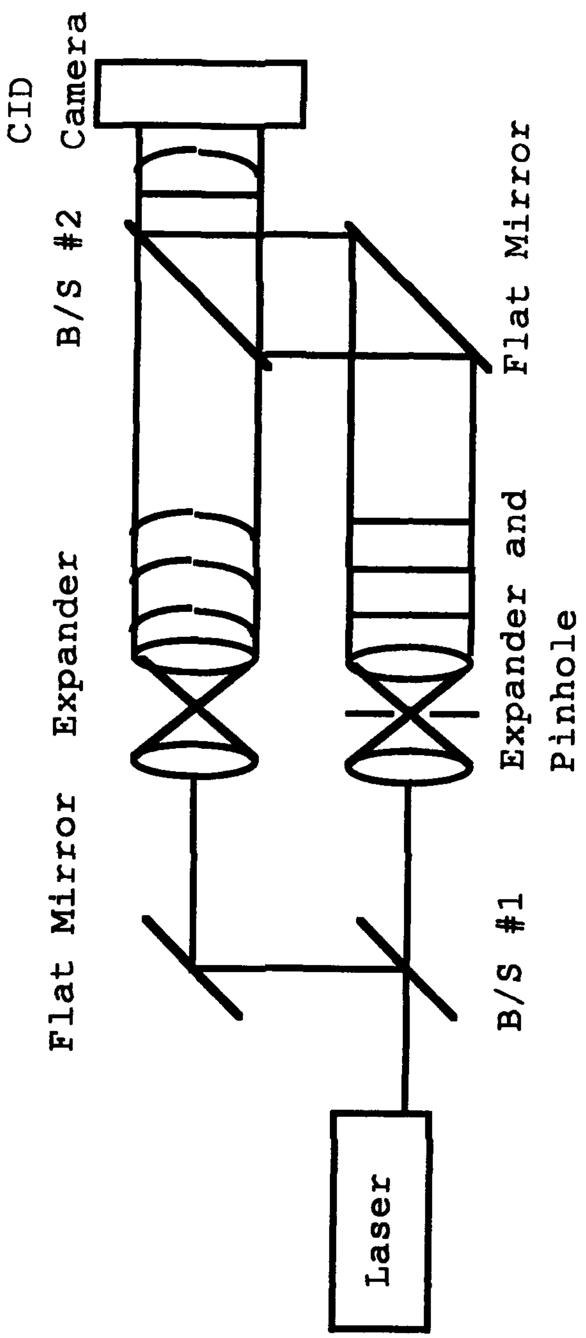


Figure 10. Mach-Zehnder interferometer modified for phase-front measurements.

was placed one focal length from the pinhole to produce the plane wave. The test arm also had an identical spatial filter but with the pinhole removed. This expanded the input beam to match the size of the reference beam. The two beam splitters were chosen to give equal transmission and reflection for the wavelength of the laser used. To get better contrast, a variable neutral density filter was used in the test beam to reduce its intensity to match that of the reference beam.

The interference patterns from the above interferometers were recorded using a frame grabbing system that integrated a CIDTEC charge injection device camera and a Z-248 computer, running Big Sky Computer Corporation's *Beamcode 5.0* software.

V. Results and Discussion

There were three main phases to the research discussed in this thesis: 1) crystal selection, 2) development of a phase conjugate interferometer to measure the phase front of a single element diode laser, and 3) development of a phase conjugate interferometer to measure the phase front of a multi-element diode array laser. Each of these is a necessary step toward the ultimate goal of this research: measuring the phase front of a ten element diode array using a phase conjugating Twyman-Green interferometer.

The interferometers used in this research utilize $BaTiO_3$ crystals as phase conjugate mirrors. Not all crystals operate equally efficiently, so each available crystal was tested and the most efficient crystals were chosen. The crystals were selected using the argon-ion laser. Of the three available lasers, this laser afforded the most efficient phase conjugation due to its shorter, visible wavelength. This laser had an additional benefit: a visible beam is easier to align than an infrared beam.

The argon-ion laser was shined into each available crystal. It delivered 28 mW of power in a 2 mm diameter spot onto each crystal. As the beam entered a crystal, fanning (the spreading out or widening of the beam) would typically occur in less than 10 seconds. The direction of fanning indicated the direction of the positive c-axis of the crystal. When the crystal was oriented properly, the beam would curve into a corner and a phase conjugate spot would form on the observation screen.

Crystals were selected based on their ability to readily provide a strong phase conjugate return. The experiment for the investigation of the crystals is depicted in Figure 9. The crystals with the fastest response times were #162-D, #163-A, and #164-E. Crystals #162-D and #164-E were both z-cut and measured 7.0 x 7.0 x 5.5 mm and 5.0 x 5.0 x 6.0 mm respectively. Crystal #163-A was a 45 ° cut crystal which measured 6.0 x 6.0 x 5.0 mm. The most efficient orientations found for these crystals are shown in

Figure 11. Each of these three crystals produced strong phase conjugate returns in under 15 seconds. Depending on the specific orientation, these crystals returned 12% to 30% of the light incident on them. Crystals #162-D, #163-A, and #164-E were chosen for use in the interferometers because it was assumed that the crystals which responded best to the visible laser would be the best candidates for the research using the infrared lasers.

The second phase of the research was to develop and validate a phase conjugate Twyman-Green interferometer, and use it to measure the phase front of the Sharp diode laser. This laser was expected to be more difficult to phase conjugate than the argon-ion laser due to its infrared wavelength. In order to observe the infrared beam inside the crystals, a CCD video camera (with the infrared filter removed) was mounted above the experimental apparatus and trained on the crystals in a closed-circuit TV monitoring system.

The first step in developing the phase conjugate Twyman-Green interferometer was to achieve phase conjugation in $BaTiO_3$. The Sharp laser was directed to the $BaTiO_3$ crystals which were selected in the experiment with the argon-ion laser. The crystals were left alone for various lengths of time ranging from 30 minutes to 15 hours in order to allow phase conjugation to occur. With each of the crystals, after approximately five minutes the beam began to fan (an early sign of phase conjugation). After another 20 minutes, the entire crystal illuminated. The crystals did not exhibit any further change, and a phase conjugate return was never observed. Although this exercise used the same crystals in the same orientation as did the argon-ion laser experiment, phase conjugation was not observed.

Scientific journals were examined in an attempt to determine a cause for the apparent failure of the Sharp diode laser to phase conjugate. An article by Bendall and Gookin (Reference #2) describes a similar experiment in which they succeeded in phase conjugating an 830 nm laser only after submersing the $BaTiO_3$ crystal in a solution which acted as an index buffer. According to Bendall and Gookin, this index buffer—glycerol—

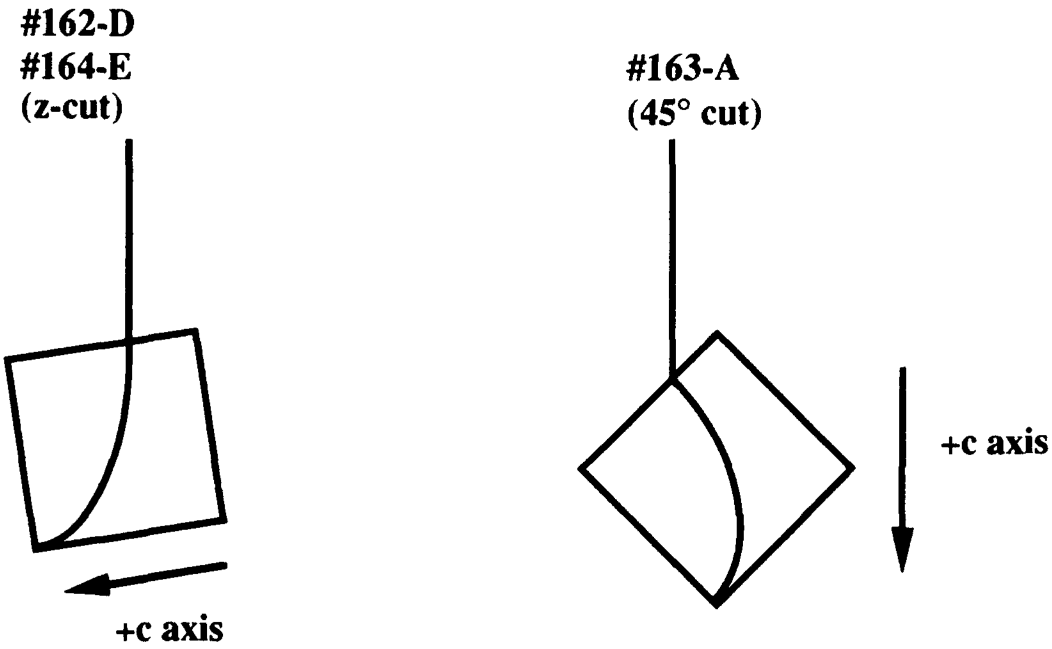


Figure 11. Configuration of the crystals which allowed the most efficient phase conjugation with the argon-ion laser.

allowed the laser beam to cross the crystal at the optimum angle of 50° relative to the c-axis. They stated that "this internal angle was necessary to compensate for the low gain in $BaTiO_3$ at 830 nm" [8]. The 50° angle can not be achieved with an air-crystal interface, therefore they used the glycerol-crystal interface which was capable of providing the necessary angle.

For the present experiment, glycerol was not available so calculations were necessary to determine if a similar solution—microscope immersion oil—might be used as an index buffer to attain phase conjugation with the Sharp laser. Figure 12 shows the geometry for the desired angle. The index of refraction for glycerol is 1.6. Using Snell's law it can be shown that Bendall and Gookin used an incident angle of 75° at the glycerol-crystal interface to achieve this angle (index of refraction for the crystal is 2.4). A similar calculation shows that this angle is not possible with an interface between microscope immersion oil (n=1.5) and the crystal. Further calculations were done to determine whether or not an angle close to 50° could be attained. Using a limiting angle of incidence of 90°, Snell's law yields a transmitted angle of 38°. This angle corresponds to an angle of 52° relative to the c-axis. It was assumed that this angle would be close enough to the optimal angle to achieve phase conjugation, so the oil was chosen as the index buffer.

Fresnel's equations [14: 102] were used to show that Bendall and Gookin were experiencing a 10% loss of incident power due to the reflection at the glycerol-crystal interface. For the oil-crystal interface, Fresnel's equations indicate that a 23% loss could be expected when an 80° incident angle was used (transmitted angle of 52° relative to the c-axis) . Although this loss is greater than that of Bendall and Gookin, it was assumed not to be a problem since the Sharp diode is capable of delivering up to 12.3 mW to the crystal. While Bendall and Gookin's loss was only 10%, they used only 2.4 mW. The Sharp's greater power should sufficiently make up for the greater loss.

Crystal #164-E was oriented in the oil to produce the 52° angle relative to the c-axis (38° from the normal). Fanning was observed within ten seconds and a phase conjugate

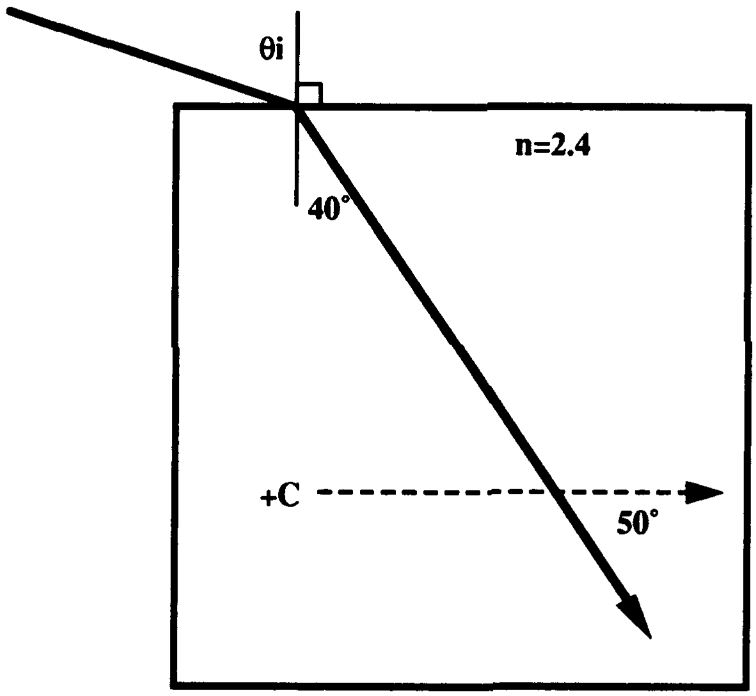


Figure 12. Geometry for ray angle calculations inside the crystal. The optimal angle of 50° relative to the c-axis is shown.

spot formed in less than one minute. Before the phase conjugate spot formed, two opposite corners of the crystal began to light up. As the corners grew bright, a diagonal beam formed between them. As the beam grew in intensity, the phase conjugate spot formed. Pictures of the crystal in the oil before and during phase conjugation are shown in Figure 13. Phase conjugation was not observed with crystal #163-A (45° cut) when it was oriented in the oil to provide a 50° angle relative to the c-axis. With this crystal, less than a 5% loss was calculated for the reflections at the interfaces. The reason for this crystal's failure to phase conjugate in this configuration can possibly be attributed to improper orientation of a 45° cut crystal. Phase conjugation with the Sharp diode was successful with crystal #164-E submerged in the oil, so this crystal was used in all subsequent research.

In order to create a phase conjugate Twyman-Green interferometer , a flat mirror was added to the existing apparatus. A schematic of this interferometer is shown in Figure 14. This interferometer was used to measure the phase front of the Sharp diode laser.

When the Sharp laser was shined into the interferometer, the input beam was conditioned by several components. An optical isolator, also called an optical diode, prevented the retro-reflections coming off the crystal and the flat mirror from interfering with the laser. A half-wave plate was used to rotate the polarization which provided an extraordinary ray for the $BaTiO_3$ crystal. A beam expander served to enlarge the interference pattern. A beam splitter divided the input beam, transmitting part of it to the flat mirror and reflecting the other part to the crystal. A focusing lens focused the beam down to a small spot on the face of the crystal. A CID camera, used in conjunction with the Beamcode program, recorded the interference patterns which were created when the two beams recombined at the beam splitter.

The fact that interference was observed indicated that light was being reflected from the crystal, but not that it was necessarily a phase conjugate return. It was possible to conduct a test to determine whether or not the reference beam created by this interferometer

Before During

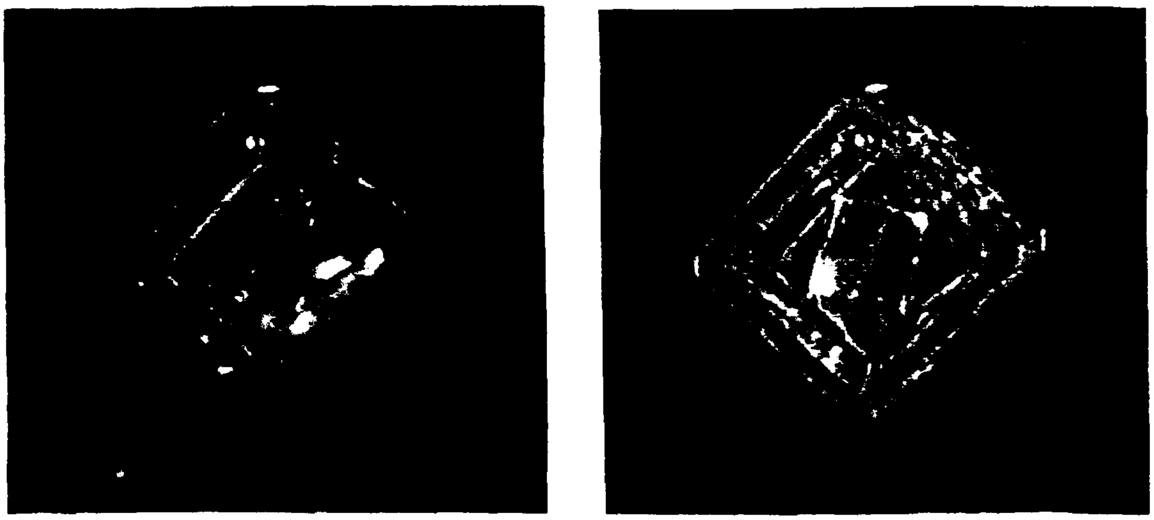


Figure 13. Phase conjugation with the Sharp diode laser. The picture on the left shows the beam crossing the crystal before phase conjugation. The picture on the right shows the crystal during phase conjugation. The crystal is submerged in an oil bath which served as an index buffer.

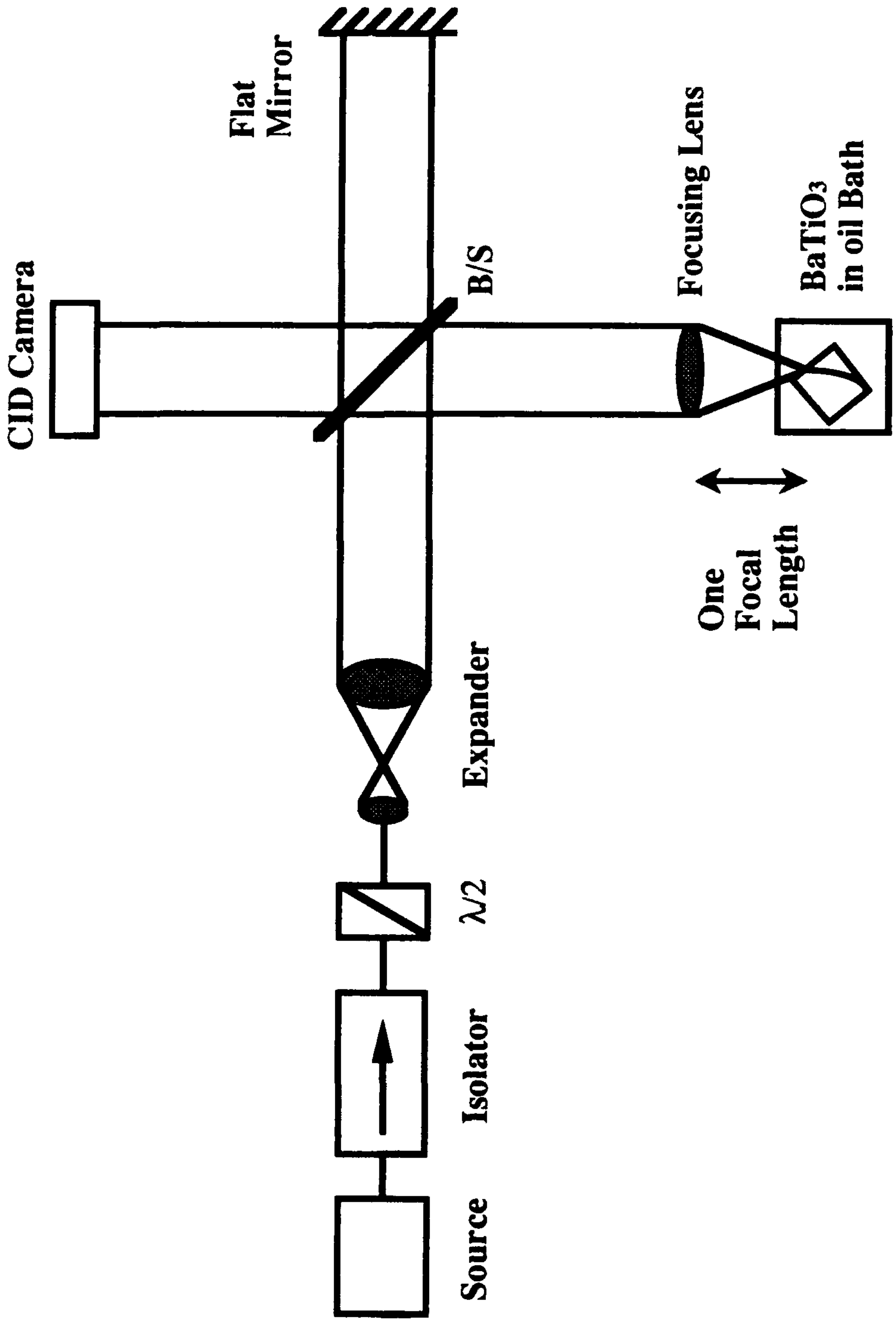


Figure 14. Phase conjugate Twyman-Green interferometer. The oil bath is necessary to achieve efficient phase conjugation with the Sharp diode.

was in fact phase conjugated. This test exploited the unique quality of a phase conjugate mirror to compensate for aberrations. A microscope cover slide—a source of aberrations—was placed in front of the flat mirror, causing an obvious change in the interference pattern. When the cover slide was placed in front of the phase conjugating mirror, the shape of the interference pattern did not change, indicating that the crystal was compensating for the aberrations and thus phase conjugating. These interference patterns are shown in Figure 15.

After verifying the phase conjugating ability of the interferometer, the phase front of the Sharp diode was measured. The beam was passed through a spatial filter with a 25 micron pinhole to remove any aberrations and an interference pattern was recorded. The resulting interference pattern would have shown any aberrations inherent in the interferometer. However, no aberrations were revealed. The spatial filter was removed and another interference pattern was recorded. This interference pattern indicated the shape of the phase front of the input beam. (If there had been sources of aberration in the interferometer, the aberrations in the first pattern would have been subtracted from the aberrations in the second to reveal any aberrations present in the input beam.) When examining the interference pattern of the beam with the filter out of the interferometer, aberrations can clearly be seen on the right side of the pattern, which indicates an aberration in the beam. The region with the aberrations was further investigated by adjusting the collimating lens to make the beam more closely resemble a plane wave. By reducing the tilt of the flat mirror, the number of fringes in the interference pattern is reduced, thus increasing the resolution. This closer scrutiny of the interference patterns showed conclusively that there are aberrations present in the beam. The series of pictures showing the aberrations with and without the pinhole in place is shown in Figure 16.

For comparison, a Mach-Zehnder interferometer was used to record conventional phase front measurements. This interferometer was set up as shown in Figure 10. The interference pattern produced by this interferometer and the Sharp diode is shown in

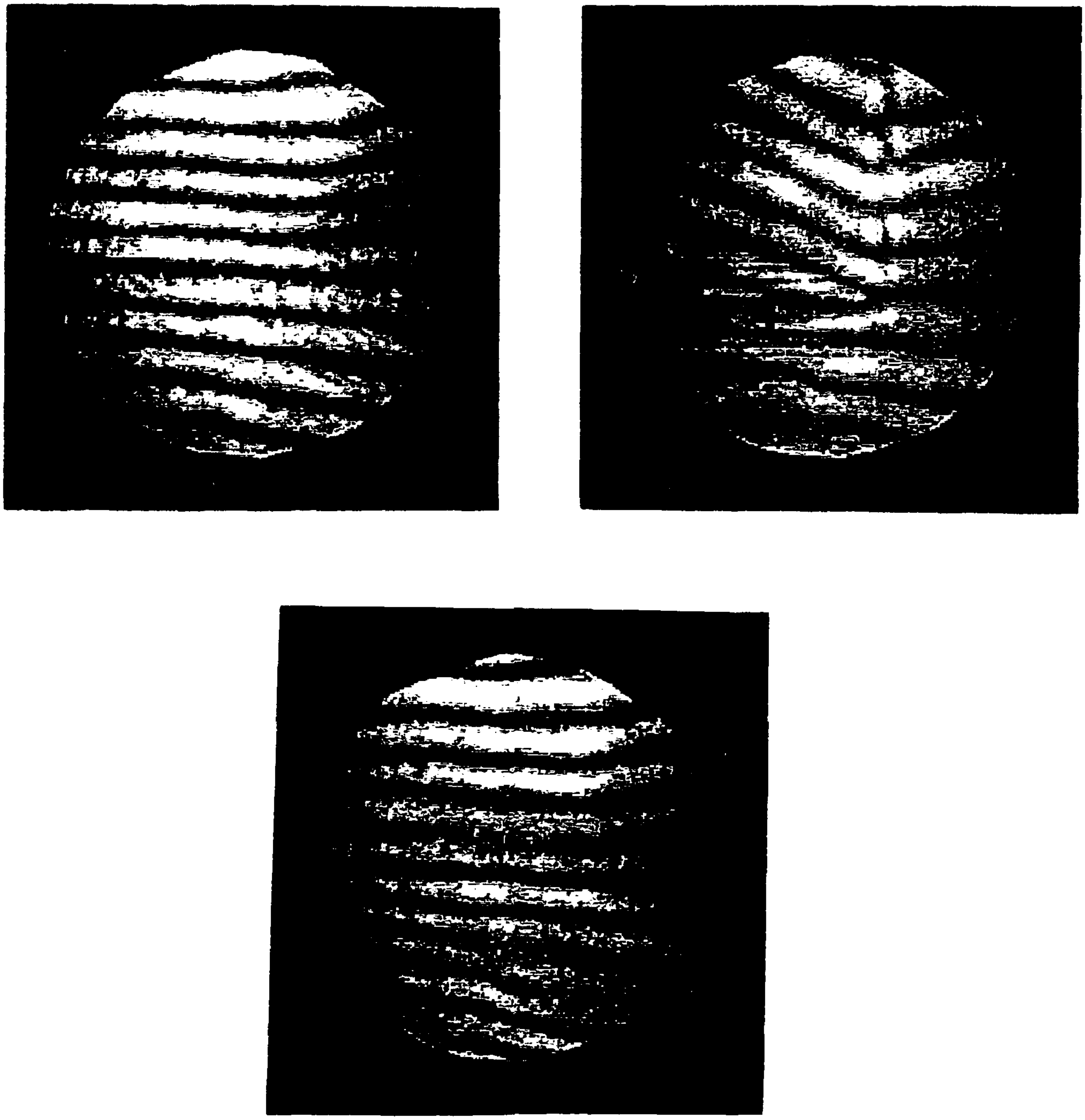


Figure 15. Validation of the phase conjugating ability of the $BaTiO_3$ crystal with the Sharp diode. The first interference pattern indicates no added aberrations. The middle pattern shows the altered interference pattern which resulted from placing a microscope cover slide in front of the flat mirror. The third pattern was recorded with the cover slide in front of the crystal. The shape of the pattern is the same as when no cover slide was used indicating the ability of the phase conjugate mirror to remove aberration.

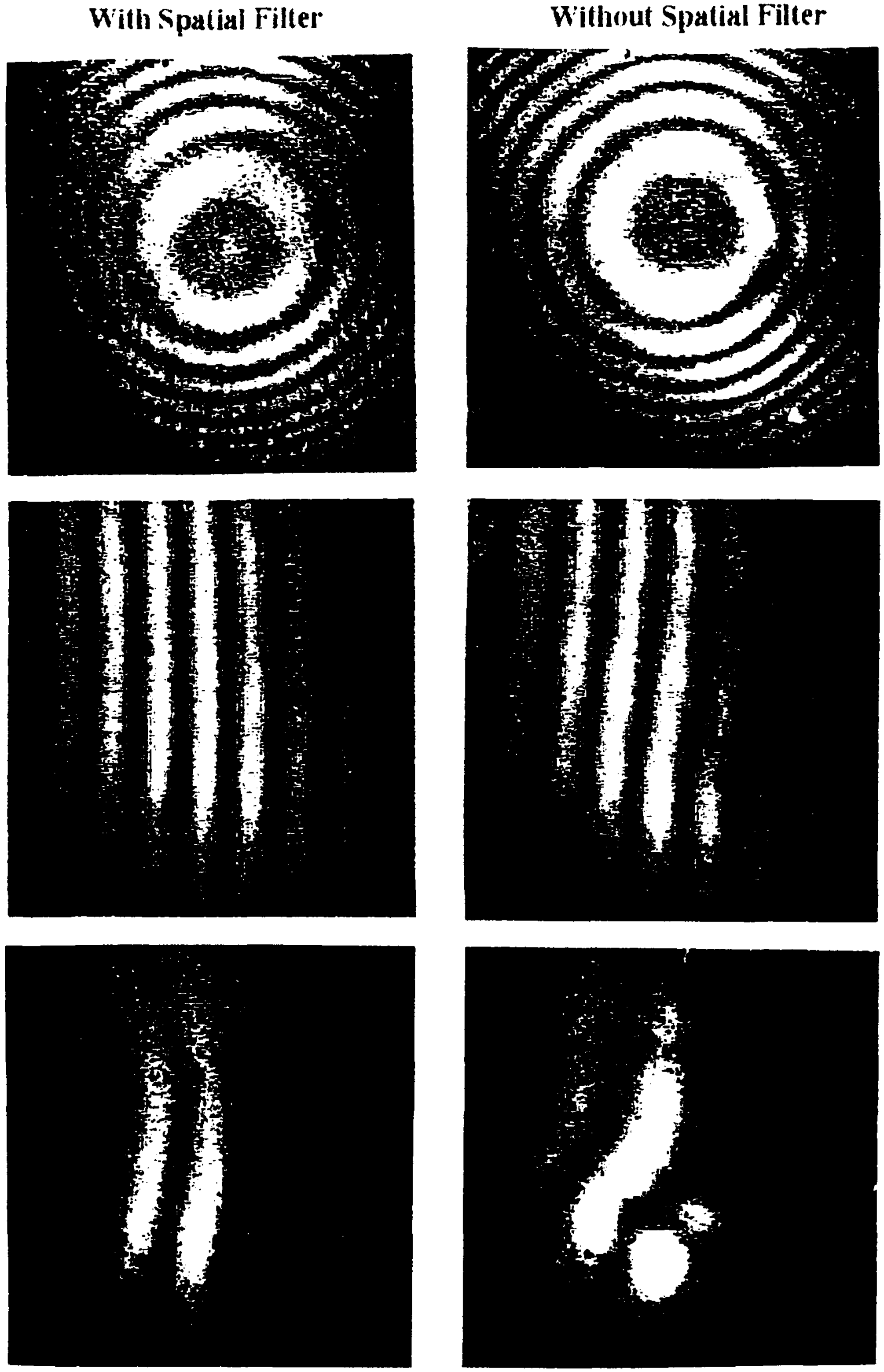


Figure 16. This series of interference patterns shows, with increasing resolution, the aberrations found in the phase front of the beam from the Sharp diode.

Figure 17. In this pattern, no aberrations in the laser beam are apparent. Since the phase conjugating Twyman-Green interferometer did show aberrations, it appears that the Twyman-Green interferometer exhibits better resolution than the conventional Mach-Zehnder.

The next phase of this research was to develop a phase conjugate Twyman-Green interferometer capable of measuring the phase front of the diode array. This was expected to be much more difficult than with the Sharp diode due to the interactions between the elements of the array and the short coherence length of this laser. The beam from the entire array was focused to a 2 mm diameter spot on the face of the crystal to see if phase conjugation would occur. The laser delivered 40 mW of power to the crystal. There was no observable effect.

Phase conjugation was attempted with the output from several individual elements. To separate the output of one element from the others, the array was imaged onto an iris diaphragm. This diaphragm was adjusted small enough to allow only the beam from one element to pass through it. Each element delivered between 3 and 5 mW to the crystal. When using a single beam, the $BaTiO_3$ crystal did show some signs of phase conjugation. As with the Sharp diode, fanning began in less than 5 minutes. However it took 30-60 minutes for the crossing beam to form between the two corners. The slower response was expected due to the lower power incident on the crystal. At this point the crystal looked very much like it did when phase conjugating the beam from the Sharp diode (see Figure 18). Note the resemblance between these pictures and the ones shown in Figure 13. However, a phase conjugate return was not observed, even after 3 days.

The Sharp diode and the diode array were examined to determine what differences were present which may have accounted for the inability of the array to phase conjugate. Parameters examined included: coherence length, mode structure, and wavelength.

Each laser lased at 830 ± 2 nm. The Sharp diode successfully phase conjugated with as low as 6 mW. The individual elements from the array only provided between 3.5

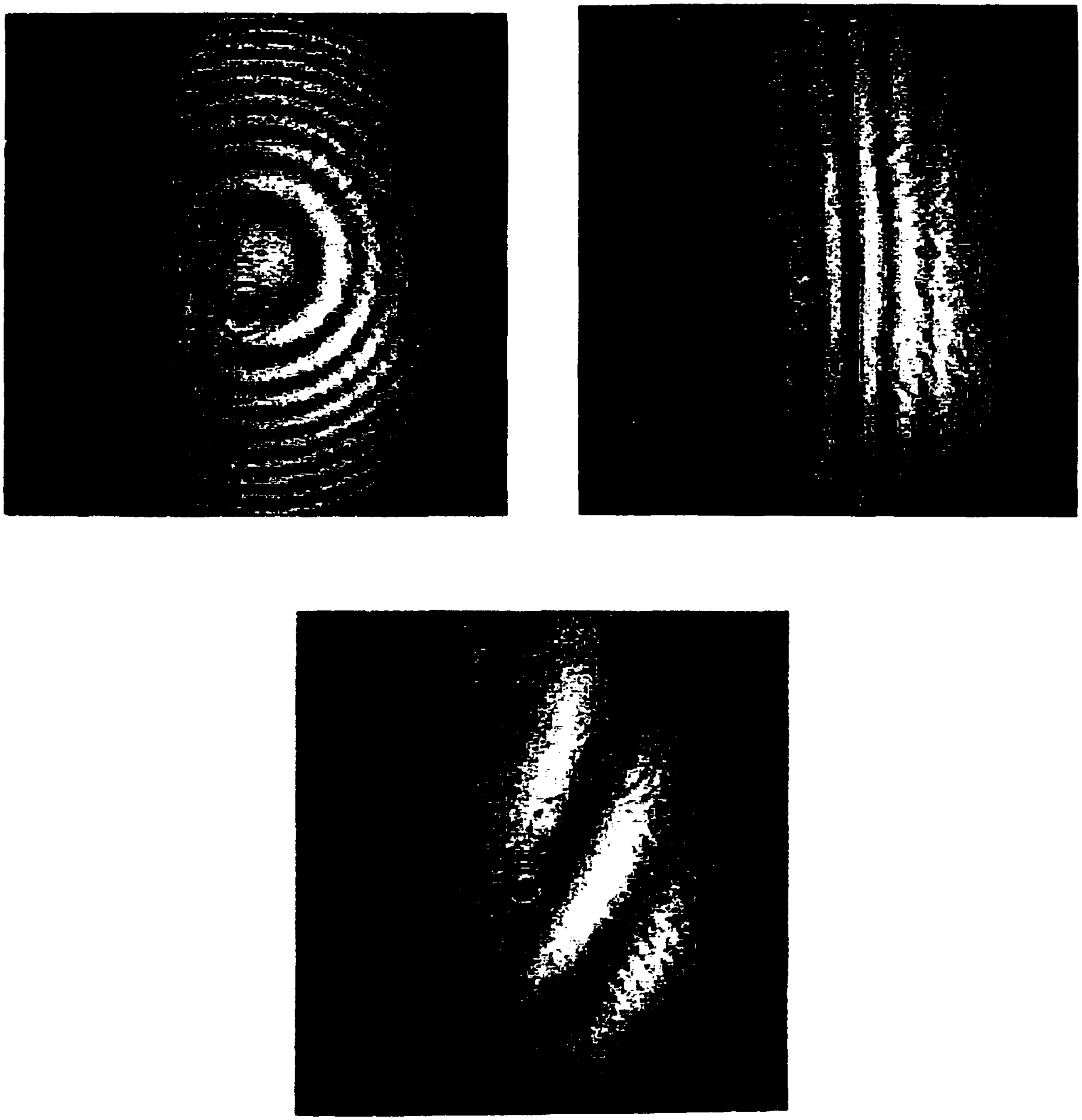


Figure 17. Interference patterns taken with the Mach-Zehnder interferometer. The aberrations in the beam are not apparent with this interferometer.

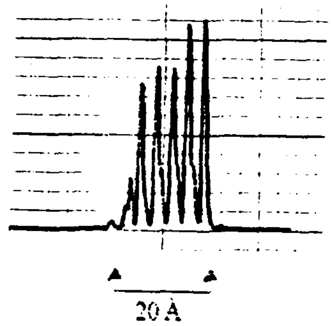
Figure 18. Attempted phase conjugation with the diode array laser. The picture shows the crystal during phase conjugation. The crystal is submerged in an oil bath which served as an index buffer.

and 5.0 mW of power to the crystal. The lower power provided by the individual elements is believed to have caused the slower response times but does not account for the inability of the individual elements to phase conjugate.

Spectral mode analysis of the infrared lasers indicated the Sharp diode to be lasing in a single longitudinal mode, while the array was lasing in multiple longitudinal modes. The array lased with 5 to 6 modes present at all operating currents. The mode structure for the two lasers is presented in Figure 19. The mode structure for the Sharp diode is asymmetric due to misalignment of the scanning Fabery Perot interferometer. This interferometer was intentionally misaligned to prevent optical feedback from interfering with the laser. This difference in mode structure is not believed to have caused the array not to phase conjugate because the multi-mode argon-ion laser did phase conjugate.

The coherence lengths of the two lasers were measured using a conventional Twyman-Green interferometer. The coherence length of the Sharp diode was found to be 95 cm. The coherence length of the a single element from the diode array was measured to be only 2 cm. The argon ion laser also was determined to have a coherence length of 2 cm. The short coherence length, in conjunction with the decreased efficiency of the longer wavelength, is believed to be the primary reason that the diode array could not create a phase conjugate return.

Diode Array



Sharp Diode

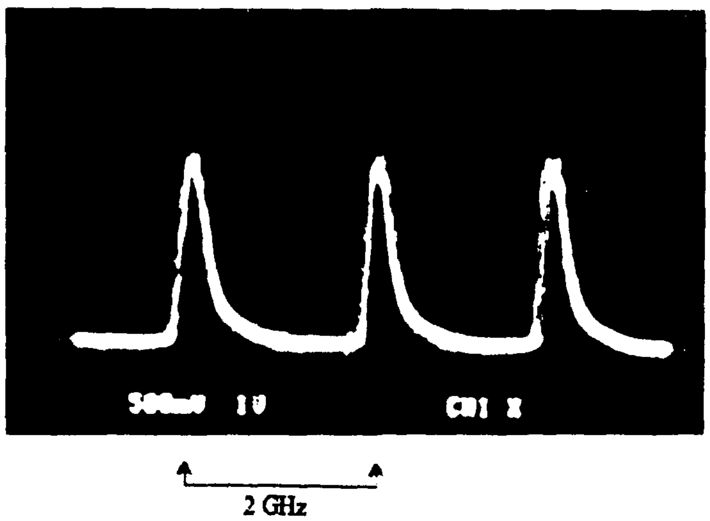


Figure 19. Mode structure of the diode array and the Sharp diode. The array was designed as a multi-longitudinal mode device. The Sharp diode was designed to operate in a single transverse mode.

VI. Conclusion

The phase conjugating Twyman-Green interferometer appears to have several advantages over conventional interferometers. It has enhanced resolution for phase front measurements and is capable of correcting aberrations caused by imperfect optics in its phase conjugating arm. The phase conjugate Twyman-Green interferometer worked well for measuring the phase front of the single mode diode laser. As expected, this type of interferometer proved to be more sensitive than conventional interferometers for measuring the phase front of an input beam. The obvious disadvantage of this type of interferometer is that it is only capable of measuring the phase front of lasers which are capable of producing a phase conjugate return. The phase conjugate Twyman-Green interferometer could not function for the multimode diode array due to the array's inability to produce a phase conjugate return.

Because this interferometer could not measure the near-field phase front of the diode array, it did not achieve the desired goal of furthering the research to control the phasing of diode arrays. While diode arrays may still be a promising device for both military and civilian laser applications, the phase conjugate Twyman-Green interferometer was not successful in advancing this research.

VII. Recommendations for Future Work

Work should be done to determine why the Sharp diode was able to phase conjugate while the single element from the diode array was not. A systematic investigation of the effect of coherence length should be undertaken in order to determine the relationship between coherence length and phase conjugation. This may be done by using a phase modulated single mode diode laser. By modulating the output of a single mode diode laser at a frequency faster than the response time of the $BaTiO_3$ crystal, the laser would appear to the crystal to be emitting over a broader bandwidth which would cause the crystal to react as if the laser had a shorter coherence length. By controlling the range of modulation, it would be possible to control the effective coherence length of the laser. This investigation could reveal information about the minimum coherence length necessary for phase conjugation for a specific wavelength.

Alternate orientations of the crystals could also be tested for their ability to phase conjugate the output from a single element of the diode array. Smaller crystals (or possibly a shorter axis of one of the crystals) could be used in hopes that the beam would remain coherent within the crystal in order to allow phase conjugation.

Bibliography

1. Hillman, P.D. and Marciniak, M. Phase locking laser diodes using photorefractive coupling. *Journal of Applied Physics 66*, 12 (December 1989), 5731-5737.

2. Twu, Y. Mode Characteristics of Phase-Locked Semiconductor Laser Arrays at and Above Threshold. *IEEE J. Quantum Electronics QE-23*(1987), 788-795.

3. Pepper, D.M. Nonlinear Optical Phase Conjugation. *Optical Engineering 21*, 2 (March/April 1982), 156-183.

4. Pepper, D.M., Feinberg, J., and Kukhtarev, N.V. The Photorefractive Effect. *Scientific American* (October 1990), 62-74.

5. White, J.O., Cronin-Golomb, M., Fischer, B., and Yariv, A. Coherent oscillation by self-induced gratings in the photorefractive crystal BaTiO3. *Applied Physics Letters 40*, 6 (March 1982), 450-452.

6. Feinberg, J. Self-pumped, continuous-wave phase conjugator using internal reflection. *Optics Letters 7*, 10 (October 1982), 486-488.

7. Cronin-Golomb, M. and Lau, K.Y. Infrared photorefractive passive phase conjugation with BaTiO3: Demonstrated with GaAlAs and 1.9-mm Ar+ lasers. *Applied Physics Letters 47*, 6 (September 1985), 567-569.

8. Bendall, I. and Gookin, D. Phase Conjugation in BaTiO3 at 830 nanometers. *SPIE 1148*(1989), 25-28.

9. Feinberg, J. Interferometer with a self-pumped phase-conjugation mirror. *Optics Letters 8*, 11 (November 1983), 569-571.

10. Gauthier, D.J. and Boyd, R.W. Phase-conjugate Fizeau interferometer. *Optics Letters 14*, 6 (March 1989), 323-325.

11. Shukla, R.P., Dokhanian, M., Venkateswarlu, P., and George, M.C. Phase conjugate Twyman-Green interferometer for testing spherical surfaces and lenses and for measuring refractive indices of liquids or solid transparent materials. *Optics Communications 78*, 6 (November 1990), 407-415.

12. Yaeli, J. Phase measurement of laser diode array radiation. *Applied Physics Letters 49*, 8 (August 1986), 427-429.

13. Cherng, C.P., Salvi, T.C., Osinski, M., and McInerney, J.G. Near field wavefront measurements of semiconductor laser arrays by shearing interferometery. *Applied Optics 29*, 18 (June 1990), 2701-2706.

14. Hecht, E. *Optics*, Addison-Wesley Publishing Company, Inc. , Second(1987).

15. Hariharan, P. *Optical Interferometery*, Academic Press Australia (1985).

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13. ABSTRACT *(Maximum 200 words)* This study demonstrated the use of a phase conjugate Twyman-Green interferometer for measuring the phase fronts of beams emitted by infrared diode lasers operating at 830 nm. This interferometer successfully measured the phase front of a single element diode laser, providing better resolution than its conventional counterpart. The phase conjugate mirror compensated for aberrations introduced by imperfect optics in the phase conjugating arm of the interferometer. This interferometer was unable to measure the phase front of a diode array due to the array's inability to create a phase conjugate return. The array's short coherence length is believed to be the main cause preventing the phase conjugate return.

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